VIII Photonic Crystals

The electronic properties of crystalline solids are determined by the atomic or molecular eigenfunctions and the periodic arrangement of atoms or molecules in the solid. Within the Born-Oppenheimer approximation the nonrelativistic electronic wavefunctions are the solutions of the Schrödinger equation with a static periodic potential. The linear *optical* properties of macroscopic solids, on the other hand, are, in the absence of external sources, determined by the Helmholz equation. For piecewise homogeneous media, the latter is in fact equivalent to the Schrödinger equation with a piecewise constant potential. It is therefore appropriate to introduce the concept of a photonic crystal, i.e. a material with periodic variations of the dielectric constant and a period of the order of a wavelength. The first step toward a photonic crystal is, of course, a photonic molecule[1], whose optical properties have been considered in chapter III. A multilayer interference filter may be considered as the simplest example of a photonic crystal, in this case a one-dimensional crystal. Whereas in the one-dimensional case a photonic bandgap is easily achieved, a threshold value of the dielectric contrast exists in the two and three dimensional case for the existence of a photonic bandgap in all propagation directions[2]. A bandgap for propagation in all three dimensions prohibits the propagation of light through the photonic crystal for a certain wavelength interval. This leads to a number of interesting quantum-optical effects with promising applications. E.g., if the crystal contains fluorescent molecules, the fluorescence should disappear within the bandgap. This is a quantum mechanical effect, because within the photonic band gap, the spontaneous emission is reduced and the lifetime is lengthened. Of special interest are photonic crystals with defects, because they allow to construct lasers with zero thresholds. The defect itself acts as a microcavity and emission is possible only into the corresponding cavity modes[3]. Moreover, the reduced mode volume leads to strong radiation-matter coupling, which leads to the appearance of quantum-optical effects equivalent to the well-known Rabi-splitting, optical nutation, etc. occurring in vacuum[45].

In the present chapter two two-dimensional photonic band gap structures are investigated by means of the commercial MAFIA program package, which is based on the FIT technique[6,7] and which was used in chapter VII to study the transmission properties of near-field optical fiber tips. The first structure is a finite two-dimensional crystal containing a defect and the second one is a microoptical element, a miniaturised Mach-Zehnder interferometer, which may be of interest for integrated-optics circuits. It makes use of the efficient guiding, which is possible in defect structures of photonic bandgap crystals[8]. The microoptical element constructed in this way, a miniaturised Mach-Zehnder interferometer may be of interest for integrated-optics circuits.

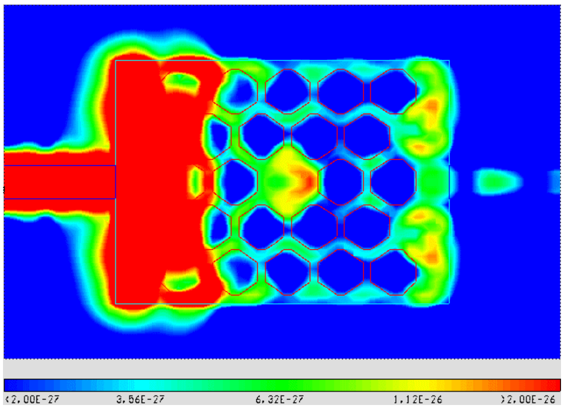

Fig. VIII.1: Photonic crystal with a defect in the center excited at a wavelength of λ=550nm (in the bandgap) by the fundamental mode of a rectangular waveguide attached to the crystal. The time-averaged intensity is shown on a logarithmic scale.

<u>Photonic crystal with defect</u>

We want to discuss a simple example of a 2-dimensional photonic crystal with a defect. A suitable structure is, for example, a thin film of GaP with an array of cylindrical holes etched into the film, because GaP has a very high index of refraction of n=3.45 at a wavelength of λ=550 nm, which is important in optoelectronics. It can be shown, that in the case of a hexagonal structure, a bandgap exists for this wavelength for a ratio of r/d between 0.45 and 0.5[9]. Here r denotes the radius of the cylindrical hole and d the shortest distance between them. In the following Fig. VIII.1, a simulation of such a crystal for a ratio r/d = 0.48 (in the bandgap) is shown. The crystal consists of a thin film of GaP, thickness d_P = 100 nm, containing cylindrical holes of diameter 2r = 203 nm in a hexagonal arrangement with a distance of d = 237 nm between the cylinder axes. The crystal is excited through a rectangular waveguide with a rectangular cross section, 100x100nm, by the fundamental mode polarized perpendicular to the film at a wavelength of λ=550nm.

It is readily recognized from Fig. VIII.1, that the light cannot propagate through the crystal, because its wavelength is inside the bandgap. The light can tunnel, however, into the defect at the center of the structure, which consists of a missing cylindrical hole. If the same crystal is excited at another wavelength (e.g. λ=1.0 µm) outside the bandgap, light propagation is possible without difficulties (not shown here).

<u>Mach-Zehner interferometer</u>

Another interesting application of a photonic crystal is the guiding of light in channels, which may have a very large curvature. An example is a Mach-Zehner interferometer based on a similar structure as that considered in Fig. VIII.1. The ratio r/d is the same, only a different number of cylinders is chosen here. Several cylinders have been removed to form two channels, which allow the propagation of light of λ=550nm. (compare Fig. VIII.2).

The intensity in the output waveguide depends very sensitively on the inter-

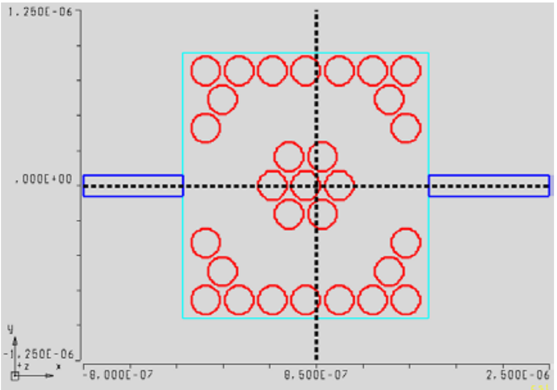

Fig. VIII.2: Structure of the device, for which the intensity field distribution was calculated. A Mach-Zehner interferometer is formed in a photonic crystal by leaving out cylindrical holes in the two-dimensional crystal in such a way, as to form to channels, where the light can propagate. The diameter of the cylinders and the distance between them as well as the cross sections of the attached waveguides are the same as in Fig. VIII.1.

ference conditions. If, for example, a contamination is deposited in one of the channels or in one of the neighboring holes, the output intensity is modified and conclusion about the nature of the contamination should be possible. The results for the (uncontaminated) interferometer are shown in Fig. VIII.3.

For a quantitative analysis, we have calculated the transmission of the perfect, but finite photonic crystal (compare Fig. VIII.4), as well as of the crystal containing the interferometer (compare Fig. VIII.5).

Fig. VIII.4 confirms, that the light within a certain frequency range ($\nu \approx$

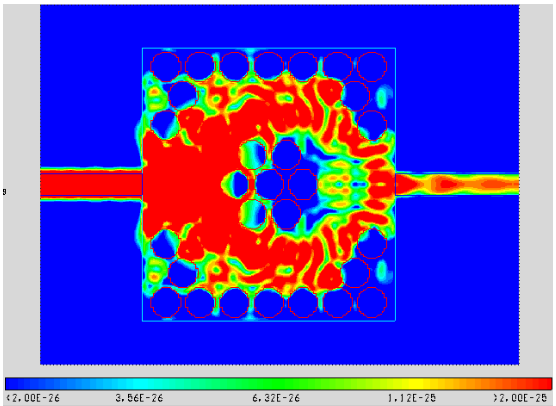

Fig. VIII.3: Intensity distribution in a Mach-Zehner interferometer in a photonic crystal (compare Fig. VIII.2), constructed from defect channels. Wavelength λ=550nm.

$1.3 \cdot 10^{14}$ s^{-1} - $\nu \approx 8 \cdot 10^{14}$ s^{-1}) corresponding to ($\lambda \approx 375$ nm - $\lambda \approx 2300$nm) cannot propagate through the photonic crystal. The band edges are relatively sharp. For

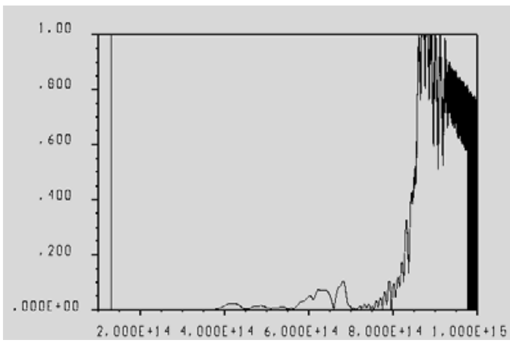

Fig. VIII.4: The frequency dependence of the transmission is shown on a linear scale for a perfect (but finite) dielectric photonic crystal with the geometric and material parameters given in Fig. VIII.1 (without defect).

frequencies outside the gap, the light is transmitted to the waveguide at the output side with high efficiency.

For comparison, the transmission of the Mach-Zehner interferometer is shown in Fig. VIII.5). Transmission within the photonic bandgap is, of course induced by the two defect channels. The transmission varies strongly within the gap, as the coupling into the output waveguide depends sensitively on the detailed intensity distribution of the standing wave forming at the output side of the interferometer.

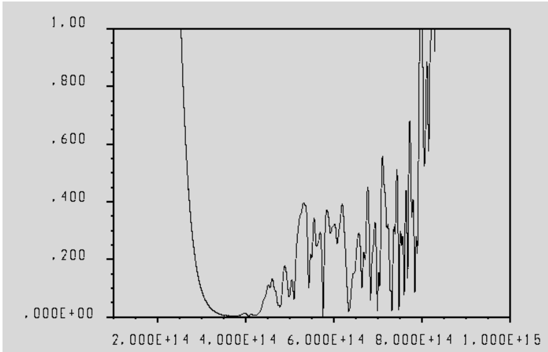

Fig. VIII.5: Transmission for a photonic crystal with an imprinted Mach-Zehner configuration. The frequency is plotted on a linear scale. The scales of the axis have the same limits as in Fig. VIII.4 in order to simplify the comparison.

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